Trauma & Orthopaedics

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Electrical conductance as the predictor of fracture healing

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Abstract

Introduction

Measurement of electrical conductance can be a useful tool for early diagnosis of delayed and non-union of fractured bone. Their role and relationship with the frequency of supplied alternating current has been studied here for the measurement of fracture healing.

Materials and methods

About 12 patients, between 18 and 50 years of age with compound fractures of bones in both legs (Gustillo's grade I and II), treatable by external fixators, without associated injuries or complications, reporting to the trauma centre of KGMU Lucknow, Uttar Pradesh, India, were treated by insulated external fixators. Electrical conductance was measured within 24 hours after the surgery and then on two weekly intervals for 10 weeks by an LCR-Q (inductance, capacitance, resistance-quality) meter on frequency of 100 Hz and 1 KHz, which also permitted measurement of conductance. The patients were then classified into 'union at week 20' and 'non-union at week 20', based on clinic–radiological assessment by three blinded clinicians. The two concordant decisions were considered as the best decision.

Results

Patients with delayed union had lower conductance than patients with normal union. Electrical conductance was able to demarcate 'union at week 20' from 'non-union at week 20' significantly at week 10 at frequency of 1 KHz (p = 0.009 at week 10) and insignificantly at (p = 0.16).

Conclusion

However, electrical conductance is highly influenced by change in frequency due to differential dissipation of bound water; it may be a useful tool for the early diagnosis of delayed union and non-union at frequency of 1 KHz.

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Introduction

Measuring the rate of fracture healing objectively and diagnosing problems like delayed union and non-union, is still an open question[1]. To diagnose these problems early, clinicians rely on subjective assessments like radiography[1], short form 36[1], RUST (radiographic union scale in tibial fractures) score[2], vibrational analysis[3], local tenderness, abnormal mobility, transmitted movement and weight bearing[4], echo tracking[5] etc. Early diagnosis may lead to change in treatment at an early stage[6] reducing the time, cost and trials of treatments to reach the desired outcome, i.e., union.

Bones are dielectric, i.e., semi-conductive in nature[2], which, when applied upon by the electrical fields, differs from the artificial conductors. In contrast to an electrical conductor, conductance of a bone varies with the frequency of the alternating current. This difference is attributed to bound water in the biological cells, which gets dissipated in a discernible manner at various frequencies yielding distinct readings[7]. Different physiological conditions and collagen intervene with this electrical conduction. Streaming potentials are sensitive indicators of tissue health related to degradation and loss of function[8,9]. Therefore, characterizations of electrical properties including electrical conductivity[10–13] are of fundamental importance in understanding the electromechanical behaviour of bones.

Binette, in his study, found that electrical conductivity of an intact humeral head bovine articular cartilage was 1.14 ± 0.11 siemens per meter (n = 11) for 1 to 2-year-old steer, and 0.88 ± 0.08 S/m (n = 9) for a 4-year-old cow. The significant difference in electrical conductivity (p = 0.00001) was due to difference in water content that diminishes with age[15] (to the best of our knowledge, it is the only reported value of conductance correlated with age and water content). Electrical conductivity on water content (porosity), i.e., volume fraction in the tissue occupied by the fluid phase is in the range of 0.65 to 0.80 S/m for uncalcified cartilage and 0 to 0.20 S/m for bone[15]. The primary charge carriers in PBS (phosphate buffered saline) and tissue fluid are sodium (Na^+) and chloride (Cl^-)[14], therefore, the change in their concentrations may also affect the values of electrical conductance. Electrical current enhances the rate of fracture healing but excessive current destroys the living tissues[16]. Therefore, there is a need to identify electrical conduction in the human bone so that exact current values can be applied to promote fracture healing and yet avoid any tissue degradation. Delayed union is a major problem in compound fractures where the patient loses the haematoma, which serves as a scaffold of fibrin for the functioning of repair cells for fracture healing[18]. This extent of loss may affect the electrical conductance. Monitoring electrical conductivity values and their change can be used to identify delayed unions early,

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which could be helpful in deciding the treatment.

The objectives of this study were:

- To determine the differences in the trend of electrical conductance in patients with delayed union and normal union at various time intervals.
- The effect of the change in frequency on the values of conductance of bone as the fracture heals.

Materials and methods

About 12 patients, 18–50 years, with compound fractures of the bone in both legs, Gustillo's grade I and II, treatable by external fixators, without associated injuries or complications, reporting to the trauma centre of KGMU Lucknow, UP, India, were treated by insulated external fixators, permitting the measurement from bone and marrow only. Insulation was achieved using pins and rods that were coated by an inert biomaterial (a derivative of epoxy), which has also been used for the insulation of the wire of the pacemaker since 1978[19]. This permitted the measurement of electrical conductance just inside the bone excluding any noise due to soft tissue. Permission for the study was granted by the Institutional Review Board. Written informed consent was obtained from the patients enrolled in the study.

Baseline characteristics were recorded (Table 2). Age, sex and date of injury of the patient were recorded. The size of the wound (circumference) was measured with the help of thread and a simple centimetre scale. The shape of wound, presence or absence of pus and contamination was assessed by the senior resident in-charge. The type of fracture and fracture of fibula were assessed with the help of pre-operative radiographs. Haemoglobin was measured in gram% using Sahli's method. Total leukocyte count (TLC), polymorphs, eosinophils, lymphocytes and monocytes were measured as cells/mm^3 using an auto analyzer.

Wounds were debrided and fractures reduced and externally fixed using epoxy-coated Schanz pins and rods. To protect the epoxy coating, the holes were drilled and tapped in the bones using normal pins which were then taken out and insulated pins were screwed in. There was no coating on the surface that penetrated the bone making it insulated from the air, skin and soft tissue. The three segments of tibia were the normal segment lying above the fracture (proximal segment), the normal distal segment lying below the fractured site and the fractured segment lying in between the proximal segment and distal segment. The lengths of the segments (proximal, distal and fracture) were also measured on post-operative non-digital radiographs in centimetres.

Electrical conductance was measured across fracture site, normal proximal and distal segments that permitted measurement due to the presence of the Schanz pins of the external fixator. Electrical conductance was measured on day 1, week 2, week 4, week 6 and week 8 across the fracture site and normal proximal and distal segments. The patients were then classified into 'united at week 20' and 'not united at week 20' after the removal of the fixator at week 10. It is to be noted that delayed union is a subjective diagnosis dependent upon clinician's perspective. We chose 20 weeks, since at least 16 weeks from the start of treatment for simple fractures should elapse before a diagnosis of delayed union can be considered[21]. Patients were classified into non united or united at 20 weeks by three blinded orthopaedic surgeons (blinded for electrical parameters, and to the decision of other clinicians). The two concordant decisions were considered as the correct decision. Measurement error for conductance was minimized by measuring the conductance in two steps: first, keeping the probes aligned as Red and Black and then reversing them and second, considering their averages as crude readings. Conductance was measured at two different frequencies of alternating current (2 micro-amperes), 1 KHz (Kilo-hertz) and 100 Hz (hertz), for finding out the relationship as this change occurs. Electrical conductance was measured in micro-siemens and standardized by the length of segment in millimetres.

Statistical analysis methods

Statistical analysis was performed using Stata Version 10 (StataCorp, Texas, USA). Baseline characteristics were compared between the two groups and p-values reported to study the possibility of confounders affecting the measurement. Generalized linear regression model for repeated time measures was applied to model conductance over three factors type, frequency and healing type measured at five time points, i.e., day 1, week 2, week 4, week 8 and week 10.

Results

Out of the 12 patients, 8 patients were 'not united at week 20' and 4 patients were 'united at week 20'. Using two different frequencies to elicit the trend in conductance values across normal segments of tibia showed lack of superimposition, as the 'fracture heals at week 20' or if the bone goes into 'not united at week 20' (Figure 1). Values for conductance at 1 KHz and 100 Hz in normal bone and fractured bone are shown in Table 1.

The baseline characteristics of the patients with 'not united at week 20' were compared with that of patients with 'united at week 20' (Table 2). There was significant difference in polymorph and lymphocyte count one day before surgery ($p < 0.05$). In patients with 'not united at week 20', mean lymphocyte count one day before surgery is significantly greater, i.e., 33.50 (±7.54) than in patients with

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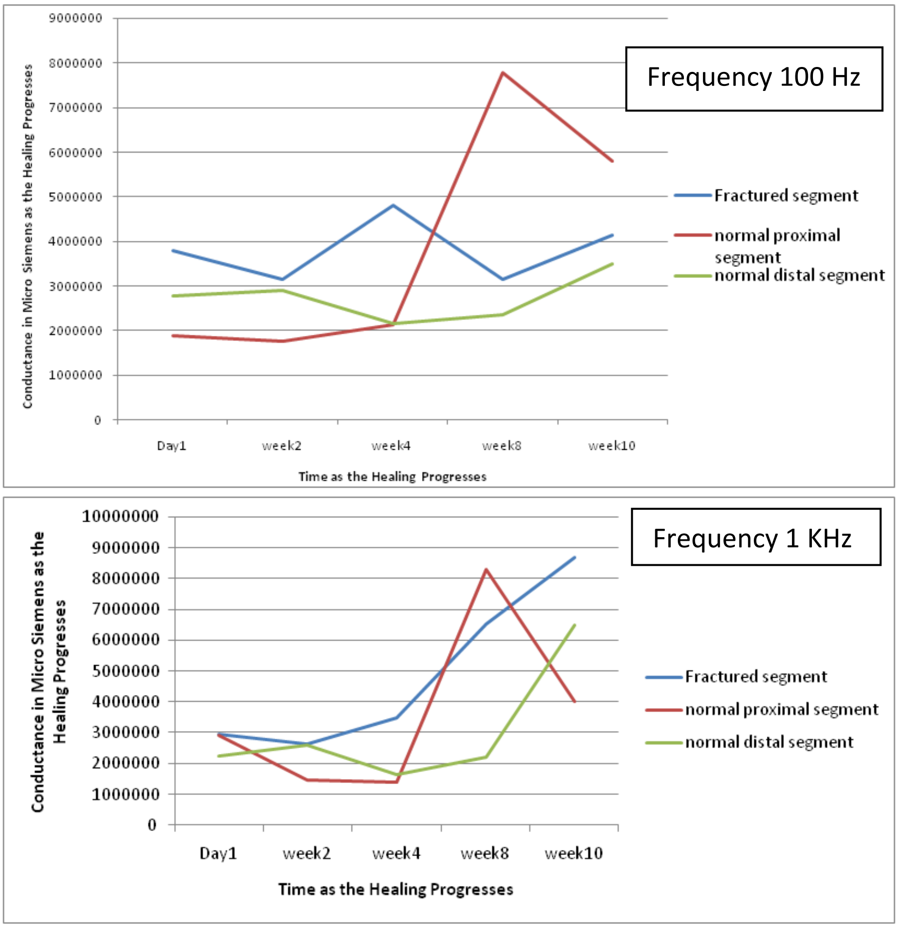

Figure 1: Trend of electrical conductance at 100 Hz and 1 KHz of normal proximal segment, normal distal segment and fractured segment of fractured tibia.

Table 1 Mean values of conductance in micro-siemens of the two normal bones and fractured bone with time at 100 Hz and 1 KHz.

100 Hz	Normal bone 1	Normal bone 2	Fractured bone
Day 1	1876894(SE-1359979)	2785187 (SE-2013777)	3784503 (SE-1953113)
Week 2	1757876 (SE-1402877)	2901499(SE-2017695)	3158577 (SE-2083196)
Week 4	2121714 (SE-1502434)	2151673 (SE-1994665)	4803047 (SE-2426106)
Week 8	7780740 (SE-6007075)	2342058 (SE-2088832)	3151114 (SE-1632457)
Week 10	5805666 (SE-5371515)	3508420 (SE-3220833)	4130806 (SE-1928527)
1.0 KHz			
Day 1	2915770 (SE-1339606)	2252954 (SE-1598532)	2980151 (SE-1568988)
Week 2	1473031 (S-1172930)	2620604 (SE-1612198)	2650311 (SE-1256501)
Week 4	1391806 (SE-1182236)	1662531 (SE-1508864)	3486552 (SE-1792125)
Week 8	8297823 (SE-5761089)	2219148 (SE-2002717)	6533455 (SE-4952081)
Week 10	4009718 (SE-3582666)	6502084 (SE-6342410)	8697704 (SE-5519825)

'union at week 20', i.e., 25.25 (±4.36). The mean polymorph count was greater in patients with 'union at week 20' (73.12 ± 4.25) as compared to patients with 'not united at week 20' (64.75 ± 7.27). There is no significant visible difference in the normal proximal segment as we change the frequency from 100 Hz to 1 KHz, but the fractured segment and the normal distal segments show visible difference in the trend line (Figure 2). However, we observed a statistically significant difference in conductance between fractures 'not united at week 20' and 'united at week 10' on 1KHz (Table 3). The conductance was lower in the 'not united at week 20' group than in 'united at week 20' group (Figure 3).

Discussion

The discrepancy in values of electrical conductance of bone when measured on two different frequencies could be related to age or different patterns of dissipation of bound water[7]. Since there was no statistically significant difference in age in the two groups in our study, we attributed the discrepancy to different patterns of dissipation of bound water at different frequencies of alternating current. However, there was a significant difference in lymphocyte count and polymorphs, which suggests that the discrepancy could have arisen due to the difference in fractures 'not united at week 20' groups and 'united at week 20' groups. Electrical conductivity is also related to relative permittivity of bone, total volumetric fraction[17] and interaction between Haversian and Volksmann canals[16]. Cancellous bone is more conductive than cortical bone[15] but here we studied electrical conductance of diaphysis of tibia; therefore, there was no confounding due to type of bone. The low value of conductance may be due to low liquid content in the fractures with 'not united at week 20' than those healing normally (united at week 20). This relationship with liquid content is also proven by the

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Table 2 Comparing baseline characteristics of patients with delayed union and union.			
Baseline characteristics	Mean &SD/counts* for delayed union ($n = 8$)	Mean &SD/counts* for union ($n = 4$)	*p*-value/*p*-chi square value*
Age	43.75 (±13.14)	37.62 (±9.84)	0.38
Sex	All were males	All were males	1
Days between injury and management	1.75 (±0.95)	2.50 (±1.30)	0.33
Days from management to discharge	15.75 (±3.68)	13.8750 (±9.6427)	0.72
Grade of compound (Gustillo's grade I, II)	3,5	1,3	0.69
Size of wound in centimetres	30.50 (±34.53)	34 (±44.15)	0.89
Shape(circular/oval/elliptical)	4,2,1	3,1,0	0.17
Contamination (present/absent)	3,1	6,2	0.88
Comminuted (present/absent)	8	4	N/A
Fibula fracture or not (yes/no)	8	4	N/A
Pus (present/absent)	2,2	6,2	0.66
Haemoglobin	9.80 (±2.28)	10.4375 (±1.90)	0.61
TLC	8950 (±3530.34)	9387.50 (±2485.63)	0.80
Polymorphs	64.75 (±7.27)	73.12 (±4.25)	0.02**
Lymphocyte count	33.50 (±7.54)	25.25 (±4.36)	0.03**
Eosinophil count	1.25 (±0.50)	1.12 (±0.64)	0.74
Monocyte count	0.50 (±0.57)	0.50 (±0.53)	N/A
Length of fractured segment (centimetres)	9.60 (±1.9)	9.67 (±4.61)	0.97
Length of the normal proximal segment (centimetres)	8.06 ± 1.6	7.50 ± 1.3	0.48
Length of the normal distal segment (centimetres)	9.00 ± 2.0	7.88 ± 1.7	0.27

** Difference is statistically significant ($p < 0.05$)

Table 3 Comparison of the mean conductance in delayed union group with union group using two frequencies.						
	Mean conductance ± SD at 100 Hz		*p*-value	Mean conductance with SD at 1 KHz in union	Mean conductance with SD at 1 KHz in delayed union	*p*-value
	Union	Delayed union				
Day 1	5496503 (SD ± 8534990)	2928503 (SD ± 6180732)	0.4	5211328 (SD ± 8102025)	1864562 (SD ± 3744519)	0.21
Week 2	407942 (SD ± 661154)	4533894 (SD ± 8669601)	0.11	392908 (SD ± 647307)	2879012 (SD ± 5218951)	0.11
Week 4	5514512 (SD ± 1090000)	4447315 (SD ± 7684499)	0.65	2641307 (SD ± 5172951)	3496496 (SD ± 6336414)	0.72
Week 8	4764175 (SD ± 9503890)	2344583 (SD ± 3051585	0.41	1510000 (SD ± 3020000)	2238491 (SD ± 2818217)	0.54
Week 10	5381576 (SD ± 1070000)	3505421 (SD ± 4390419)	0.16	1570000 (SD ± 3130000)	5209670 (SD ± 1060000)	0.009*

* Difference is statistically significant ($p < 0.05$)

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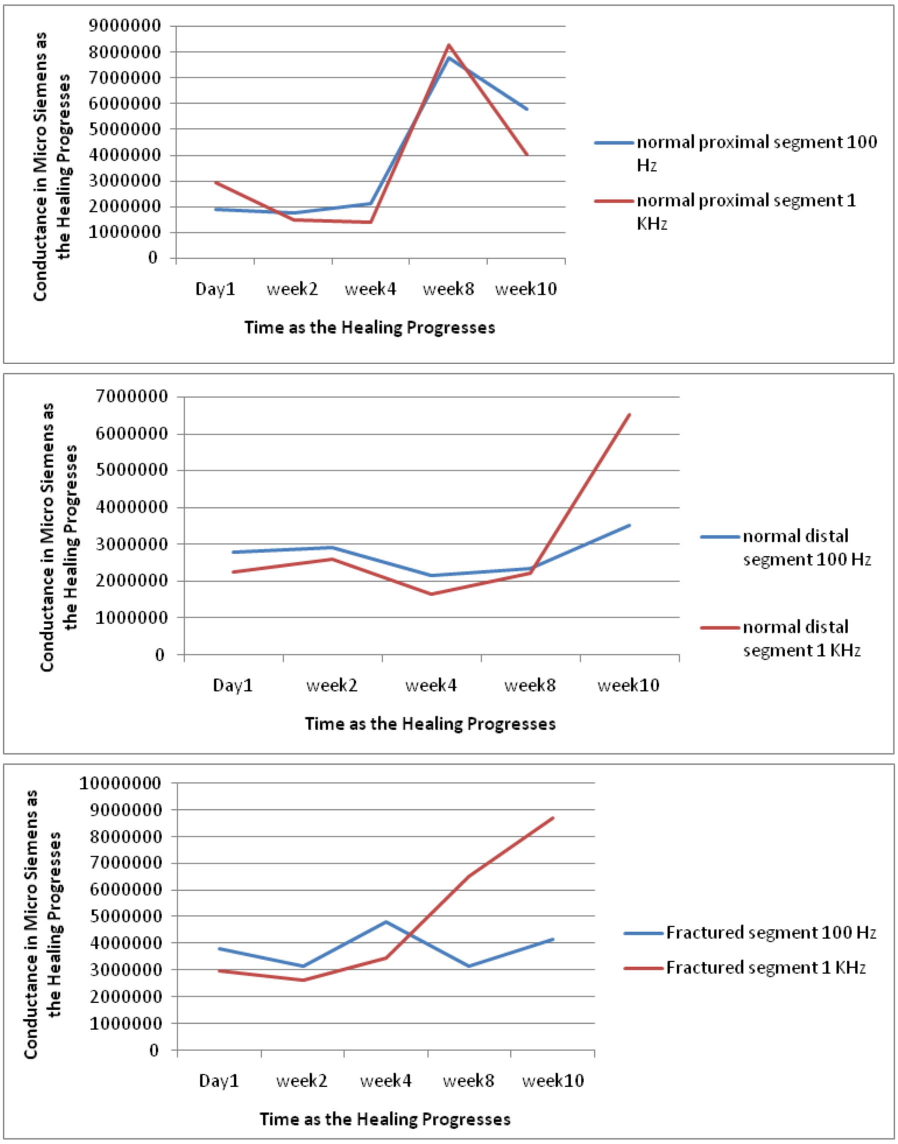

Figure 2: Comparing change in electrical conductance over time as the healing progresses.

conductance of proximal and distal segments, which did not electrically behave in a similar manner as the blood supply[17] and water content are different[16] in the two normal segments. Difference in cross-sectional area can also play a major role in understanding the discrepancy in the two normal segments of fractured tibia[6]. The discrepancy in values at two frequencies could also be due to different breaks in hydrogen bonding of the bound water at different frequencies[7]. Further study of these frequency-related phenomenon can give useful information on the electromechanical behaviour of bone as the fracture heals which, in turn, can be helpful in devising a suitable method for the early diagnosis of delayed and non-unions based on electrical conductance.

An important trend seen in our study – though still required to be studied further – is that measuring conductance at 1 KHz frequency was able to differentiate fractures 'not united at week 20' from 'united at week 20' as early as 10 weeks for injury due to compound fractures. However, if the sample size may increase, this differentiation can become more prominent at other weeks (2nd week being the next best time as p = 0.11 for differentiation) before the 10th week. Lymphocyte and polymorph counts are required to be studied at each point of electrical data collection. Electrical conductance may be different on account of different lymphocyte and polymorph counts, a finding which no one has reported till date. We also confirm the finding of in vitro studies stating that values of conductance are highly dependent upon change in frequency[21].

Conclusion

Measurement of electrical conductance as the fracture heals may be used for early identification of delayed union and non-unions. Measuring conductance at 1 KHz frequency at 10 weeks rather than at 100 Hz can demarcate non-united fractures from united fractures at 20 weeks. Discrepancy in values of electrical conductance due to differential dissipation of bound water at the two frequencies should be further studied.

Limitations

A serious limitation to our study is lack of adequate sample size but since this is the first study of its kind on humans, the error is deliberate as the objective of the study was to collect baseline data for future reference. This lack of sample size is reflected by high values of standard error and standard deviation. A future study with an adequate sample size might lower the confidence limits. Another limitation of the study was that we did not take into account possible confounder like th cross-sectional area of bone and its density, unequal number of patients in the two groups. The importance of the study is its ability to depict that electrical conductance may be used for the

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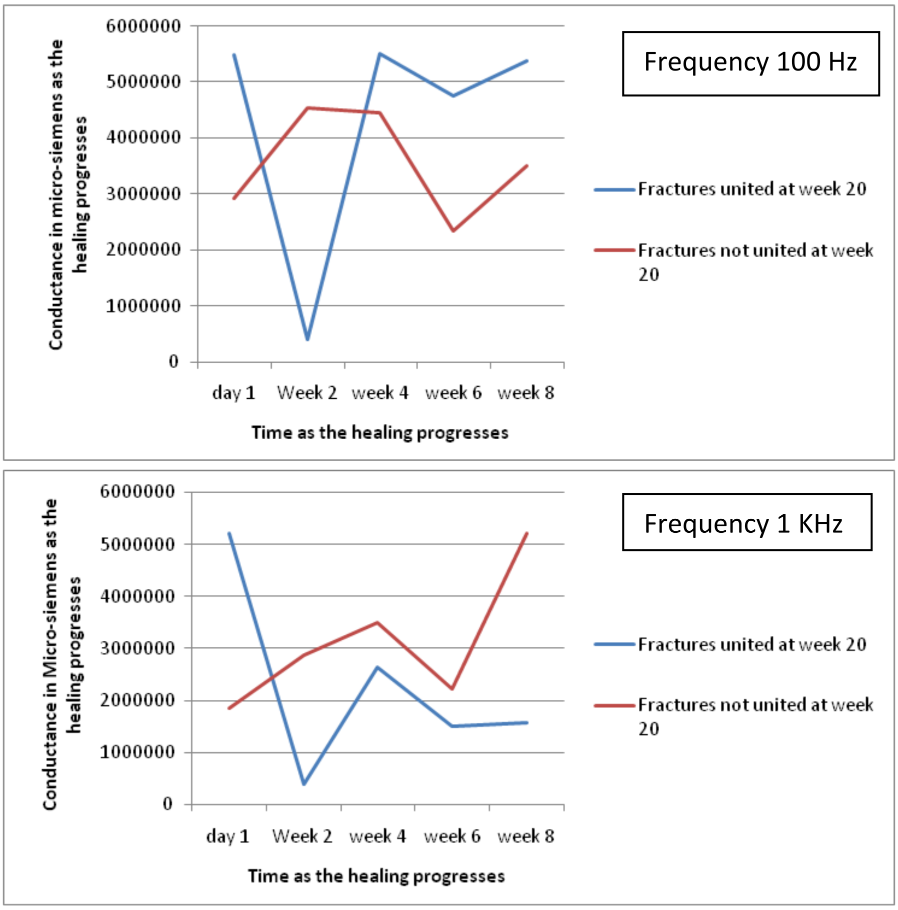

Figure 3: Comparing change in conductance over time of fractured segment at two frequencies based on classifications, 'union after week 20' and 'union at and before week 20'.

diagnosis of delayed unions early. However, we accept studies with much more robust design are required to confirm our finding. Lymphocyte and polymorph counts are required to be studied at each point of electrical data collection. Research with large sample size is required to create generalizable Z-scores for depicting union and delayed unions based on electrical conductance as the fracture heals.

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Abbreviations list

Hz, hertz; KHz, kilo-hertz; PBS, phosphate buffered saline; RUST, radiographic union scale in tibial fractures score; TLC, total leukocyte count

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